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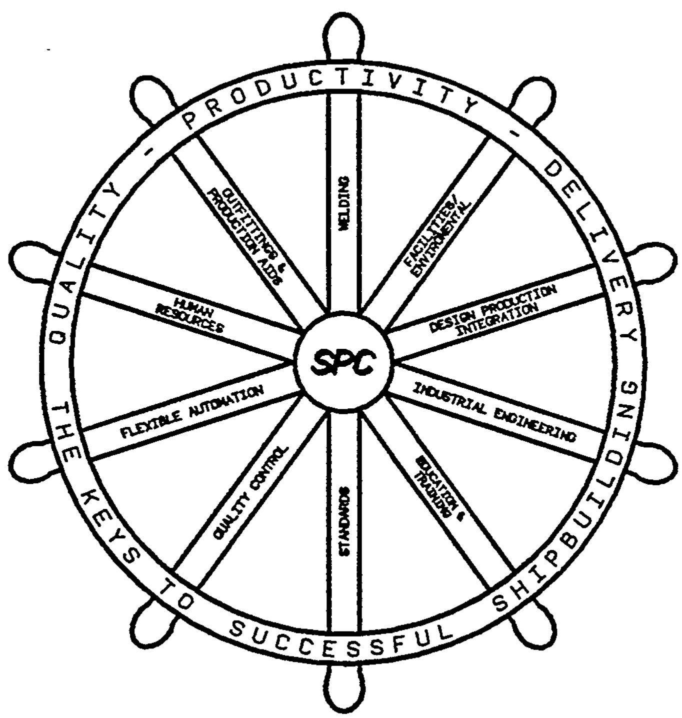

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Comparative Design of Orthogonally Stiffened Plates for Production and Structural Integrity

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ABSTRACT

Five configurations of orthogonally stiffened plates are studied to find structurally feasible cost optimal structures. First, size optimization is performed, with plate thickness and standardized beam cross section as discrete design variables. Total cost – including weight and work content - is used as an optimization criterion. Constraints include secondary/tertiary stress limits computed by Finite Element Analysis (FEA), three modes of buckling instability due to primary stresses, and producibility constraints dictated by standardization. The cost effect of structural volume due to cargo capacity loss is assessed. Next, shape optimization is performed to improve the optimal plates obtained by size optimization. A third discrete design variable - the stiffener spacing - is introduced. One weight, one work content, and one total cost optimum are identified for four of the five configurations. The overall best design and the opposite effects that variation of weight and work content have on the stiffened panel shape are discussed

NOMENCLATURE

A_3,A_5	cross section areas of stiffened plates 3 and 5
CERW	Cost Equivalent Relative Weight
C_3,C_5	material cost for stiffened plates 3 and 5
DOF(s)	degree(s) of freedom
D_x/ D_Y	plate rigidity in x/y direction
D_{xy}	plate torsional rigidity in xy plane
E	modulus of elasticity of isotropic material
Ex/Ey	modulus of elasticity of orthotropic material in x/y direction
FE(M/A)	Finite Element (Method/Analysis)
G / G_{XY}	shear modulus of isotropic/orthotropic material
K	ratio of labor rate to material rate
N	life of ship in years
NCD	Net Difference in Cost
r	rate of return adjusted for time value of money
R	freight rate per cargo tonne
t	plate thickness
z	distance form the middle plane of the plate to the mean neutral surface of the 6_x stresses

Greek Symbols

AQ	loss in carrying capacity per hip
n	an effficiency factor to account for costs of additional cargo capacity
nt	number of trips per year at full load capacity
V	Poisson's ratio of isotropic material
Vx/Vy	Poisson's ratio of orthotropic material in x/y direction
6a/6y	allowable/yield stress

INTRODUCTION

Orthogonally stiffened plates constitute as much as 50% of steel hull structural elements and dominate the total cost and production time. Consequently, their structural integrity and total cost - including material and production cost – must be analyzed carefully in order to produce the best design. Shipyard practice has established several widely accepted configurations of stiffened plates. Winkle and Baird (1) identified five conventional configurations by surveying shipyards. Even though shipyards assessed those designs as structurally equivalent discussers (1) pointed out that this was not the case. The authors of this paper have shown by Finite Element Analysis (2,3) that in four of those five configurations (Figures 1-5) the maximum secondary and tertiary stresses exceed their limit set at 75.8 MPa (11000 psi).

To rationalize the comparison of the five stiffened plate configurations, structurally equivalent designs are identified, and an optimum is found for each

configuration. In the first section of this paper, structural equivalence is established by setting a common upper stress limit of 75.8 MPa (11000 psi) for the secondary and tertiary bending stresses. The remaining stress to reach the allowable limit of 206.9 MPa (30000 psi) – yield stress of 248.2 MPa (36000 psi) reduced by a 20% safety factor – is considered as the primary stress limit, and used as the lower limit for critical buckling stress, σ_{cr}. In the second section, a total cost model for stiffened plates is suggested, using the CERW (Cost Equivalent Relative Weight) method introduced by Moe and Lund (4). Production algorithms are developed to compute the total number of man-hours needed to fabricate each stiffened plate. In the third section, the structurally equivalent cost optimal design is calculated for each configuration. Basic geometric characteristics of each configuration are preserved in the (size) optimization process. In the fourth section, the five size optimal and structurally equivalent stiffened plates are compared on the basis of weight, fabrication and total cost. In the fifth section, the effect of the cargo carrying capacity on the lifetime cost of stiffened plates 3 and 5 is added. Finally, shape optimization is performed. The weight, work content, and relative weight optima are found for stiffened plates 1,2,4, and 5. Three discrete design variables – the stiffener spacing, the thickness of the plate, and the size of the stiffeners – are used in the optimization process. All optimal configurations considered are structurally equivalent. The cost optimal stiffened plate 3 found by size optimization cannot be subjected to shape optimization because certain geometric constraints make its shape unique.

STRUCTURAL ANALYSIS OF FIVE STIFFENED PLATE CONFIGURATIONS

Structural Equivalence

The five stiffened plates (Figures l-5) which are studied in this section are all 10.7m (31.5 ft) long by 9.5m (31.17 ft) wide and constructed entirely of mild steel. They are loaded by a hydrostatic pressure due to 3m (9.84 ft) of water head. The boundary conditions are taken in such a way as to represent actual ship conditions. In general, the keel and longitudinals are continuous through the transverse bulkhead, and conditions are symmetric with respect to the bulkhead; thus the 1ongitudinal members are assumed to be fixed at the bulkhead. In general, side framing is less stiff than bottom transverse members so that transverse members may be considered simply supported at a ship's side. The stresses occurring in marine structures are divided into three categories, primary, secondary, and tertiary stresses. A complete FE model of each stiffened plate is used for calculation of the secondary and tertiary stresses. So, for those stresses an upper limit has to be defined (based on available data and engineering judgment) which leaves adequate stress margin for the primary stresses which are the most important stresses in marine structures. Primary stresses can cause buckling of ship panels. Those stresses are not calculated in this work because they are application specific; that is they depend on the size, weight distribution, and midship section of the ship. In this paper, by considering the strength properties of the steel σ_y = 248.2 MPa (36000 psi) and a safety factor of 20%, a limit of 75.8 MPa (11000 psi) is chosen as an upper limit for secondary and tertiary stresses. Thus, a configuration will be acceptable if and only if the combined secondary and tertiary stresses are equal to or less than 75.8 MPa (11000 psi), and the remaining stress margin to reach 206.9 MPa (30000 psi) – allowed for the primary stresses – does not cause buckling. If the critical buckling stress of a configuration is less than the primary stress margin, then the failure mode is the buckling mode. So, the equivalence of strength is based on the two loading conditions and the five failure modes (1, 11) listed below:

Loadings:

1. In-plane load due to primary stresses
2. Lateral load due to secondary and tertiary stresses

Failure modes:

1. Plate bending due to lateral load (secondary and tertiary stresses)
2. Stiffener bending due to lateral load (secondary and tertiary stresses)
3. Overall stiffened plate buckling due to primary in-plane load
4. Stiffener tripping due to primary in-plane load
5. Plate buckling due to primary in-plane load

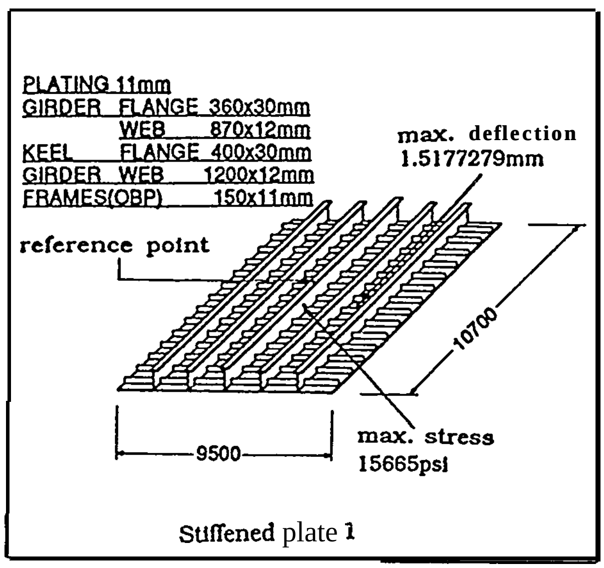


Figure 1. Characteristics of stiffened plate 1 (modified from ref. 1)

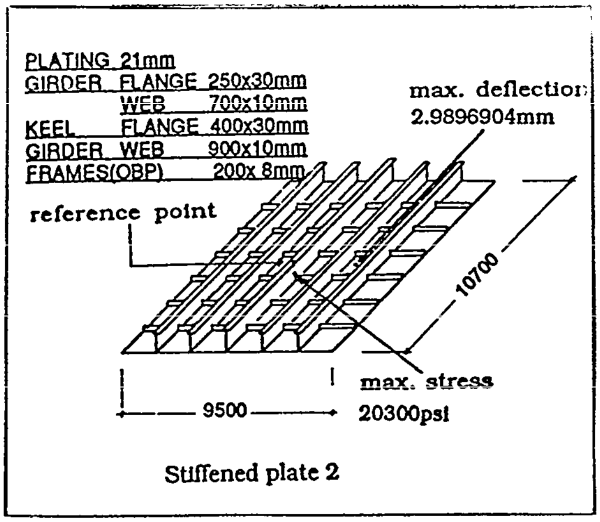


Figure 2. Characteristics of stiffened plate 2 (modified from ref. 1)

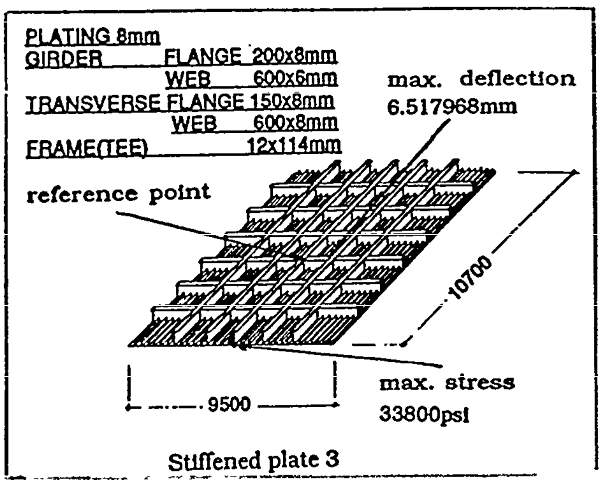


Figure 3. Characteristics of stiffened plate 3 (modified from ref. 1)

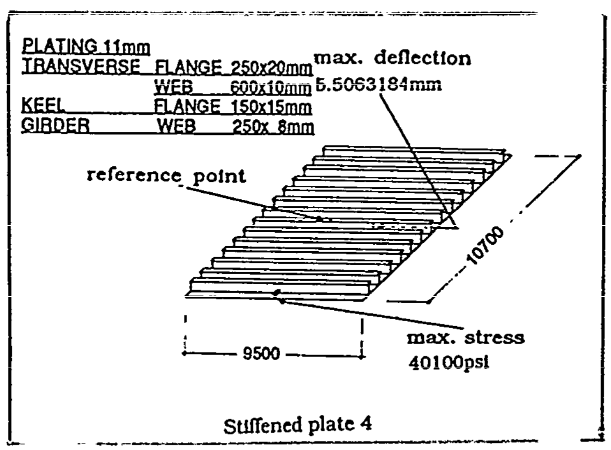


Figure 4. Characteristics of stiffened plate 4 (modified from ref. 1)

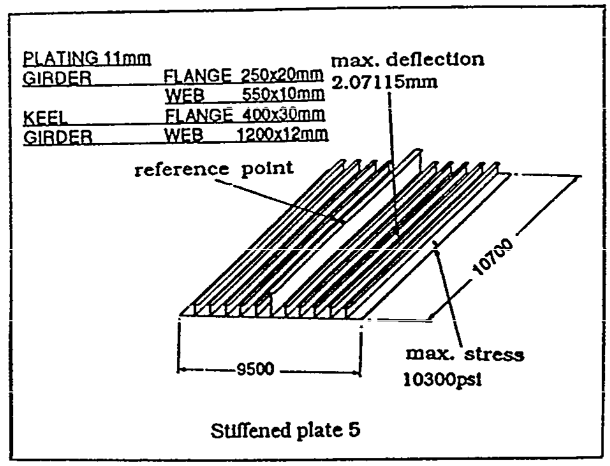


Figure 5. Characteristics of stiffened plate 5 (modified from ref. 1)

Secondary and Tertiary Stress Analysis

Three structural methods for calculation of secondary and tertiary stresses in stiffened plates by FEA are used in this paper: (i) a complete FE model, (ii) a two-dimensional grillage using effective breadth (equivalent stiffness concept) (5), (iii) orthotropic plate theory (6, 7). These three methods imply the use of a computer program capable of solving structural problems by the FE method (8).

The complete finite element model method and the method of effective breadth are used for configurations 1, 2, 4, and 5. The complete finite element model method and the method of orthotropic theory are used for configuration 3. Although only the complete FE model method is used for calculation of the secondary and tertiary stresses, the other two methods are applied in order to establish confidence in the FEA results (deflection) of the complete model by making comparisons to FEA results (deflection) using the other two methods, and to identify the best among these three methods by assessing the computational accuracy as a function of the number of DOFs and the required CPU time.

FEA of complete model: For the complete FEM model, quadrilateral plate and beam elements are used for the modeling of plates and stiffeners, respectively. The nodal points are placed at the middle plane of the plate elements. The beam element neutral axis is not on the plate neutral axis. The resulting additional stiffness is taken into account by using the offset option of the FEA program (8). Continuity of adjacent elements is simulated through the boundary conditions. The uniformly distributed load caused by a 3m (9.84 ft) hydrostatic pressure is applied directly on the plate element nodes.

FEA using the effective breadth method: In the 2-dimensional finite element grillage approach for

analyzing an orthogonally stiffened plate, the structure is converted to an equivalent grid of beams with neutral axes on the same plane. The stiffness of these beams include the corresponding equivalent plating. There are two different definitions of effective breadth based on two different concepts. The first is the breadth of the plate which – when used in calculating the moment of inertia of a section - gives the correct uniform stress at the junction of the web and the flange, using simple beam theory (9). Thus, it allows for the shear lag effect due to transmission of the lateral load to the web of a beam, and then to the flange of the beam by means of shear in the plane of the flange. The second concept – which is adopted in this paper-is the effective breadth of the plate which is independent of the applied load, and corrects the beam properties to produce a deflection that is nearly equal to that of the actual structure (5, 10).

FEA using orthotropic plate theory: Orthotropic theory replaces the plate and stiffeners with an equivalent orthotropic homogeneous plate of constant thickness. This plate has dtiferent rigidity properties in the two orthogonal directions corresponding to the stiffener directions. Thus, the orthotropic plate cannot be equivalent to the actual structure in every respect (6, 7). Equivalence may be based on either the deflection or one of the strain components at some plate point. The mean difference in deflections of the actual and equivalent plates maybe used for that purpose.

Initially, the rigidities of the equivalent orthotropic plate are calculated horn the following formulas:

$$D_x = \frac{Et^3}{12(1-v^2)} + \frac{Etz^2}{(1-v^2)} + \frac{EI_x}{s} \quad , \qquad (1)$$

$$D_y = \frac{E[h(y)]^3}{12(1-v^2)} \quad , \qquad (2)$$

$$D_{xy} = \frac{G}{6}\left(\frac{dh^3}{s}\right) \quad , \qquad (3)$$

where the rigidity in the x-direction (longitudinal), D_x, is the summation of the rigidity of the plate (fust term), plus the rigidity of the frames in the x-direction due to their offset with respect to the middle plane of the plate (second term), plus the rigidity of the repeating section in the x- direction (third term). The rigidity in the y-direction (transverse), D_y, is produced from equation (2) where the plate thickness t was replaced by h(y), the total thickness of the plate-stiffener combination subject to the limitation mentioned in reference (7).

The relations between the rigidities of the equivalent orthotropic plate and the elastic moduli E_x, EY ‘ ‘XY for the orthotropic plate are given by equations (4)-(6)

$$D_x = \frac{E_x t^3}{12(1-\nu_x \nu_y)} \quad , \qquad (4)$$

$$D_y = \frac{E_y t^3}{12(1-\nu_x \nu_y)} \quad , \qquad (5)$$

$$D_{xy} = \frac{G_{xy} t^3}{12} \quad . \qquad (6)$$

The rigidities for the orthotropic plate are derived based on equivalence of strain energy (7).

Buckling Analysis due to Primary Stresses

In this section, the buckling calculations are shown for the five stiffened plates. All the calculations are conservative and are based on the theory described in reference (11).

Stiffened Plates 1 and 2: These plates are stiffened both longitudinally and transversely. First, a check must be performed to find whether the transverse stiffeners have enough rigidity to provide nearly unreflecting supports to the longitudinal stiffeners. If the transverse stiffeners are not rigid enough, the panel may undergo gross panel buckling, in which case the transverse stiffeners buckle with the longitudinal. On the other hand, if the transverse stiffeners are sufficiently rigid, the stiffened plate between them is a simply supported longitudinally stiffened plate, and can be analyzed by the methods used for stiffened plate 5 below. For stiffened plates 1 and 2, it was found that the transverse stiffeners do not provide unreflecting supports. The minimum transverse rigidity ratio 7_y/7X to prevent gross panel buckling is :

$$\frac{\gamma_y}{\gamma_x} = \frac{B^4}{\pi^2 C a^4}\left(1+\frac{1}{p}\right) \quad , \qquad (7)$$

where y_y = E1y/Da, Y_x = EIX/Db ; a,b are the transverse and longitudinal spacings, respectively; D is the plate rigidity; C = $0.25+2JK^3$, where K is the number of longitudinal subpanels: L and B are the length and width of the stiffened plates and p is the number of longitudinal stiffeners.

Because of the small rigidity of the transverse stiffeners,, the gross panel buckling is checked. The two stiffened plates are idealized as orthotropic plates by “smting” the bending rigidity of the stiffeners over the region of the plating. The critical gross buckling stress is:

$$(\sigma_{ax})_{cr,gp} = k_0 \frac{\pi^2 \left(D_x D_y\right)^{1/2}}{B^2 \left(t + \frac{A_x}{B}\right)} \quad , \tag{8}$$

where ko=(m2/p2)+(2Hl(D.DY)V2 ~+(P2/m2) * H i the toksional rigidity of the orthotropic plate, $\rho = \left(L/B\left(D_y/D_x\right)^{1/4}\right)$ is the virtual aspect ratio, m isthe integer nearest o p ,t is the thickness of the plate, and Ax is the area of each longitufinal stiffener. The above orthotropic theory approach can be used only when the number of transverse stiffeners is large. For a small number of transverse stiffeners the orthotropic plate approach is not appropriate. In that case, the transverse stiffeners are neglected (conservative approach) and configurations 1 and 2 are examined as longitudinally stiffened plates, as in the case of stiffened plate 5.

Stiffened Plate 4: In this case, it is also found that the transverse stiffeners do not provide unreflecting supports. For this reason, the strength of the snong longitudinal stiffener in buckling and tripping is examined first. It is found that this stiffener has a very large critical buckling and tripping point. For that reason, it is assumed that it provides a simple support to the transverse stiffeners at the middle. Thus, only half of the stiffened plate is examined.

For a large number of transverse stiffeners, the orthotropic approach is used to compute the critical gross panel buckling stress. The rigidity in the longitudinal direction is taken equal to the rigidity of the plate only. For a small number of transverse stiffeners, the critical buckling point of the plate between the transveme stiffeners is computed w

$$(\sigma_{pl})_{cr} = k \frac{\pi^2 D}{b^2 t} \quad , \tag{9}$$

where k is the buckling coefficient depending on the boundary conditions and the aspect ratio of the plate. Stiffened plate 3 was not examined, because based on the discussion in reference (l), this stiffened plate is at least twice as strong as stiffened plate 4 which has been already examined.

Stiffened Plate 5: This is a longitudinally stiffened plate. So, it has to be ensured that: i) Overall buckling (stiffeners buckle along with the plating) does not precede plate buckling, and ii) the torsional rigidity is large enough to prevent local stiffener buckling (tripping). For the overall buckling, the critical buckling stress for a simply supported plate with stiffeners is:

$$(\sigma_a)_{cr} = \frac{\pi^2 E}{\left(\frac{L}{\rho}\right)^2_{eq}} \quad , \tag{1o}$$

where L/p is the slenderness ratio of the stiffener together with an effective width b of the plate, P^2= (lx)/(% + bt), AX is the cross-sectional area of the stiffener only, and Ix is the moment of inertia of the stiffener with an effective width b of the plate. Also, it has to be ensured that $(\sigma_a)_{cr} > (\sigma_{pl})_{cr}$ so that the overall buckling does not precede plate buckling. A simple check for tripping of the longitudinal stiffeners can be performed by the following formula:

$$(\sigma_{aT})_{cr} = \frac{\pi^2 E}{12 + 4\frac{A_w}{A_f}} \left(\frac{b_f}{a}\right)^2 \quad , \tag{11}$$

where A_w and Af are the areas of the web and flange respectively, and bf is the width of the flange.

COST MODELING OF STIFFENED PLATE

Production Algorithms

The data used for the development of tbe production task algorithms (Tables I-V) are taken from references (1, 12, 13, 14, 15). The man-hours are obtained by traditional work study methods corresponding to performance applied to an efficiency of 1007o, and do not allow for normal periods of rest, environmental, and psychological effects of carrying out the task. For this reason, additional operation factors (1.6 for welding [13], 1.15 for cutting, grinding, blasting and painting [13, 14]) are included. The construction algorithms also include man-hours for preparation of the welding, cutting, grinding, blasting and painting machines, layout and pitching of the plates, transportation

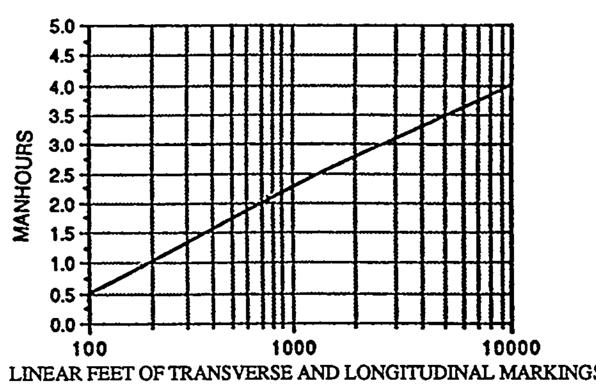


Figure 6. Time for marking (15)

jobs, marking of the panel (Figure 6), fitting and tackingof the stiffeners, etc. The construction sequence includes the following five steps described in Tables I - V, respectively (i) Flat panel sub-assembly, (ii) Flat panel marking, (iii) Stiffeners assembly and fitting to the panel, (iv) Welding of the stiffeners to the panel, and (v) Sandblasting and painting (with epoxy primer) of the panel.

Finally, the layout time calculation is based on the following

Total Layout Time = Setup Time+ Marking time,

Setup Time = 1.072 Man-hours,where the marking time is given in Figure 6.

Total Cost Modeling

In this section, the weight/cost comparison of the five stiffened plates is performed. It is assumed that the material rates are equal for all parts of the designs under consideration. The variable cost equation is the one used in reference (1}

Variable cost = (material weight* material rate)+ (man-hours * labor rate). (12)

The variable cost can be normalized to a Cost

Equivalent Relative Weight (CERW) (4) by dividing through by the material rate as follows

CERW (tome)= (material weight) (tonne)+ (K * man-hours) (tonne), (13)

where the normalizing factor K is

$$K = \frac{\text{labor rate}}{\text{material rate}} \left(\frac{\text{cost/manhour}}{\text{cost /tonne}} \text{ or } \frac{\text{tonne}}{\text{manhour}} \right) \quad (14)$$

This formulation is unique because it makes possible studying of the effkct of varying K, and can be applied to different areas of the world. Choosing a suitable

SEQUE.	ACTIVITY	OBJECT	MAN-HOURS (ref. 13 or as shown)	APPLIED PER
1	set-up	CM-45 portable burning machine	0.243	plate
2	preheat	plate	f_1(plate thk.,bevel ang)	plate
3a	burn (straight)	plate	f_2(plate thk.)	burning length
*3b	burn (bevel)	plate	f_3(plate thk.,bevel ang)	burning length
*3c	turn	plate	0.5 (1)	job
*3d	burn (bevel)	plate	f_3(plate thk.,bevel ang)	burning length
4	clear	shop floor	1.0 (1)	job
5	transport by pallet	plates	0.292 (1)	job
6	layout-pitch	plates	1.096	two plates
7	set-up	automatic submerged -arc welding job	0.213	job
8	set-up	automatic submerged -arc welding job	0.254	seam
9	butt weld	plate seams	f_4(plate thk.) (12)	welding length
10	weld pick-up	seams	0.029	seam
11	turn	panel	0.5 (1)	job
12	set-up	automatic submerged -arc welding job	0.254	seam
13	butt weld	plate seams	f_4(plate thk.) (12)	welding length
14	weld pick- up	seams	0.029	seam
15	transportation	chip/grind tools	0.134	shift
16	set-up and tear down	work area	0.189	seam (two sides)
17	chip/grind scars	plate seams	0.053	welding length
18	turn	panel	0.5	job
19	chip/grind scars	plate seams	0.053	welding length

* For plate thickness greater than 1.27 cm (0.5 in)

Table I: Flat panel sub-assembly

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 15)	APPLIED PER
1	set-up	marking process	1.072	job
2	mark	panel	f_5 (total marking length, Fig. 3)	job

Table II: Flat panel marking

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 13 or as shown)	APPLIED PER
1	set-up	hand torch	0.073	stiffener
2	preheat	web/flange	f_6 (plate thk.)	stiffener
3	burn	web/flange	f_7 (plate thk.)	cutting length
4	transport by pallet	webs/flanges	0.292 (1)	job
5	collect	plate lifting gear	0.252 (1)	job
6	position T-fashion	plate>8.33ft long	0.236 (1)	plate
7	align T-fashion	plate>8.33ft long	0.13 (1)	plate
8	fillet weld	flange to web	f_8 (web thk.) (12)	welding length
9	transportation	chipping/grinding tools	0.134	shift
10	set-up and tear down	work area	0.189	seam
11	grind edge	stiffeners	0.066	welding length
12	set-up	work place	0.154	per shift
13	fit and tack	frames	0.013	frame length
14	fit and tack	stiffeners	2.606	stiffener

Table III: Stiffeners assembly and fitting to panel

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 13 or as shown)	APPLIED PER
1	Fillet weld	frames, stiffeners	f_9 (plate thk.) (12)	welding length
2	Fillet weld	penetrations	f_{10} (web thk.) (12)	welding length
3	transportation	chip/grind tools	0.134	shift
4	set-up and tear down	work area	0.189	seam
5	chip fitting and tacks	frames	0.113	frame
6	grind edges	frames	0.003	frame welding length
7	chip fitting and tacks	stiffeners	0.143	stiffener
8	grind edges	stiffeners	0.066	stiffener welding length
9	grind	penetrations	0.066	penetration welding length

Table IV: Welding of stiffeners to panel

SEQUENCE	ACTIVITY	OBJECT	MAN-HOURS (ref. 14)	APPLIED PER
1	set-up	blasting procedure	0.9919	job
2	blast	panel	f_{11}(panel area)	unit area
3	set-up	painting procedure	0.5168	job
4	paint	panel	f_{12}(panel area)	unit area

Table V: Flat panel sandblasting and painting

value for the normalizing factor K is critically important. This analysis considers the effects of K for two values, 0.05 and 0.1. Caution is recommended regarding the interpretation and units of factor K. This factor reflects the varying labor and material rates of the international construction business. The use of a higher K value represents high labor and overhead costs. Also, the units tome/man-hour do not imply any productivhy measure.

STRUCTURALLY EQUIVALENT COST OPTIMAL STIFFENED PLATES

For the variation of the standardized beam cross sections, all 190 Bethlehem structural tees included in reference (16) and the 7 standardized beam cross sections given in reference (1) are considered. For the variation of the thickness of the plate, only integer numbers in millimeters are included in the analysis. The optimality criterion (objective function) in this section is the total cost of production and materials defined in the next section.

Optimal Sizing of Stiffened Plate 1

The strength analysis of stiffened plate 1 is performed first by a complete FEM model and then by the method of equivalent stiffness (effective breadth) with FEM. The geometric characteristics of the plate and the stiffeners are shown in Figure 1. Finite element models are prepared for both methods, and the variation of the deflection is observed at a reference point (only for the complete FEM method), as a function of the CPU time and the number of grid points (hence, the number of degrees of freedom) (2). Table VI shows the final choice for the characteristics of the complete FEM model for all 5 stiffened plates. It is found that the required number of grid points and degrees of freedom for the method of effective breadth are 430 and 1219, respectively. The CPU time was 220sec. Final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 1. Results for the location and the numerical vrdue of the maximum deflection for the method of effective breadth were derived in (2).

The maximum stress for the beams is equal to 108 MPa (15665 psi). From the definition of structural equivalence, it is concluded that this configuration is not acceptable. Also, it is found that the replacement of the transveme stiffeners with stiffeners of type WT8X13 (16) and the decrease of the plate thickness from 1 lmm to 5mm gives a configuration which has maximum stress 73.8 MPa (10700 psi) for the beams, and 41.4 MPa (6000 psi) for the plate. The longitudinal stiffeners of the original design (Figure 1) are optimal. Even though a small further decrease of the plate thickness is feasible (small stress in the plate), the thickness is not decreased because, (i) it is assumed that 5mm is the smallest acceptable thickness, and (ii) such change would result in increase of the beam stress to a level above the limit of 75.9 MPa (1 1000 psi). The optimally sized stiffened plate 1 which will be considered for comparison later (Table VII) has the same longitudinal stiffeners, plate thickness equal to 5mm (1.97 in), and WT8X13 as transverse stiffeners. The above configuration, for unchanged longitudinal stiffeners, is the optimum with respect to the total cost. It should be remembered that the geometry (number and spacing of the stiffeners) was left the same as in the initial configuration.

Optimal Sizing of Stiffened Plate 2

Similar strength analysis is performed for stiffened plate 2. Table VI shows the results of the deflection convergence process for the complete FEM model. The corresponding required number of grid points and degrees of freedom for convergence for the method of effective breadth are 295 and 741, respectively. The corresponding CPU time is 117.3 sec. Final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 2. Final results for the location and thenumerical value of the maximum deflection for the method of effective breadth were derived in (2).

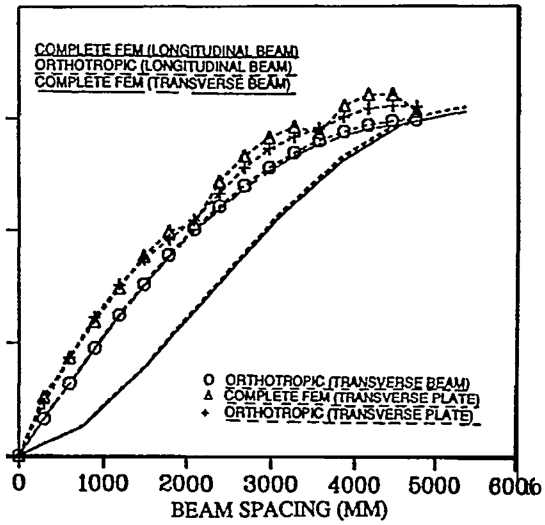
	Plate #1	Plate #2	Plate #3	Plate #4	Plate #5
Deflection (mm)	0.347	0.700	5.91	4.65	0.275
Number of grid points	775	724	975	969	1225
Number of DOFS	2059	1917	2483	2585	3289
CPu (see)	408.8	400.6	590.5	631.8	701.2

Table VE Convergence of reference point deflection for complete FEM models

The maximum stress for the beams is equal to 140 MPa (20300 psi), which implies that the above structure is not acceptable. It is found that replacement of the transverse stiffeners with the stiffeners of the type WT9X20 (16) and the decrease of the plate thickness from 21mm (8.27 in) to 13mm (5.12 in) produces the optimally sized plate 2, which has maximum stress 74.51 MPa (10805 psi) for the beams, and 61 MPa (8850 psi) for the plate. The longitudinal stiffeners of the original design (Figure 2) are optimal. The optimal stiffened plate 2 has the same geometry, the same longitudinal stiffeners, plate thickness equal to 13mm, and WT9X20 as transverse stiffeners. This configuration is actually the overall optimum with respect to the total cost, as shown in Table VII.

Optimal Sizing of Stiffened Plate 3

For the strength analysis of stiffened plate 3, the complete FEM model and the method of orthotropic plate theory are used. Table VI shows the results of the deflection convergence process for the complete FEM model. The corresponding number of grid points and degrees of freedom for the orthotropic theory FEM model are 975 and 2483, respectively. The CPU time is 576,3 sec. For the application of orthotropic theory, it is assumed that only the longitudinal frames are lumped with the plate to obtain the equivalent orthotropic plate. Final results for the location and the numerical value of the maximum deflection, the maximum stress, and the lccation of the reference point for the complete FEM method are shown in Figure 3. To compare the two methods, the deflection along (i) the middle stiffeners in both directions and (ii) the plate at the middle in the transverse direction were derived in (2). The strain energy ob@ned from the complete FEM model is 3.59 x 10^6 Nt.mm (31,754 Ibf*ft). The result from the orthotropic theory is 3.5 x 10^6 Nt.mm (30,958 ft-lbs). This result and Figure 7 show that the two methods of analysis produce similar results. The maximum stress for the beams is found to be equal to 233 MPa (33800 psi) which proves that the above shucture is not acceptable. Replacement of the longitudinal stiffeners (girders) with the stiffeners of the type: flange 250 x 30mm (9.84 x 1.18 in), web 700x 10mm (27.56 x 0.39 in); and reduction of the plate thickness from 8mm to 5mm produces the optimal sizing which has a maximum stress of 71 MPa (10300 psi) in the beams, and 30 MPa (4350 psi) in the plate. The longitudinal hues and the transverse stiffeners were found to be optimal. Thus, the optimum for stiffened plate 3 has the same geometry, and the same transverse stiffeners and longitudinal frames as the original design in Figure 3; plate thickness 5mm, and longitudinal girders with flange 250 x 30mm (9.84 x 1.18 in) and web 700 x 10mm (27.56x 0.39 in).



ure 7. Deflection comparison of complete FE model to FEM using orthotropic theory modeling for stiffened plate 3.

ıal Sizing of Stiffened Plate 4

For the strength analysis of stiffened plate 4, the complete FEM model and the method of equivalent stiffness (effective breadth) are used. Table VI shows the deflection convergence process for the complete FEM model. The last column describes the selected model. The corresponding number of grid points and degrees of freedom for the method of effective breadth are 505 and 1543, respectively. The CPU time is 235.7. The final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 4. Final results for the location and the numerical value

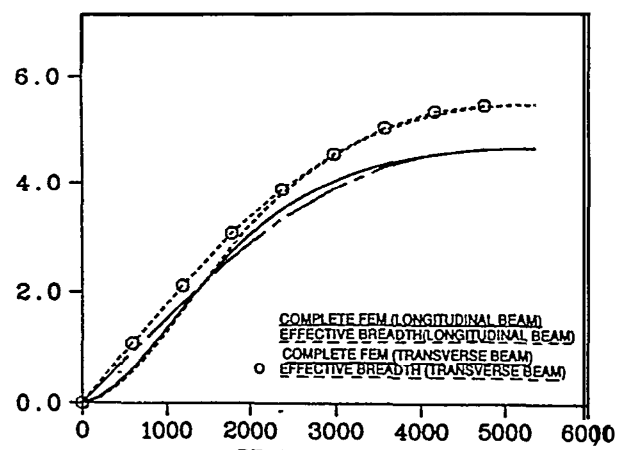


Figure 8. Deflection comparison of complete FE model to FEM using effective breadth

of the maximum deflection for the method of effective breadth were derived in (2). Figure 8 shows that the two methods of analysis produce similar results.

The maximum stress for the beams is equal to 276.5 MPa (40100 psi), which is much higher than the 75.9 MPa (11000 psi) limit. Replacement of the longitudinal stiffener with the stiffener of the type: flange 400 x 30mm (15.75 x 1.18 in) and web 1200x 12mm (47.24 x 0.47 in); decrease of the plate thickness horn llmm (0.43 in) to 8mm (0.32 in); and replacement of the transverse stiffeners with stiffeners of the type: flange 250 x 20mm (9.84 x 0.79 in) and web 550 x 10mm (21.65 x 0.39 in), gives the optimally sized plate 4, which has a maximum stress of 74 MPa (10730 psi) in the beams, and 55.2 MPa (8000 psi) in the plate.

Optimal Sizing of Stiffened Plate 5

Similar strength analysis is performed for stiffened plate 5. Table VI shows the results of the deflection convergence process for the complete FE model. The required number of grid points and degrees of freedom for convergence for the method of effective breadth are also 1225 and 3289, respectively. This is so because the plate stiffness is simulated in the transverse direction by small transverse stiffeners having the same bending rigidity with the plate. The CPU time was reduced to 581.7 sec. The final results for the location and the numerical value of the maximum deflection, the maximum stress, and the location of the reference point for the complete FEM model are shown in Figure 5. Final results for the location and the numerical value of the maximum deflection for the method of effective breadth were derived in(2).

The maximum stress in the beams and plate was found to be equal to 65.5 MPa (9500 psi) and 71 MPa (10300 psi), respectively, so the structure is acceptable and optimum with respect to the total cost.

WEIGHT, FABRICATION, AND TOTAL COST COMPARISON OF THE FIVE OPTIMAL STRUCTURES

After replacing the initial stiffened plates shown in Figures 1-5 with structurally equivalent plates – which are also individually optimized from the total cost point of view - it is possible to proceed to a weight/cost comparison of the stiffened plates. Table VII presents the relevant results for the five structurally equivalent size-optimal stiffened plates.

Work content and cost equivalent relative weight vary inversely to the weight of these structures. Stiffened plate 3 is the lightest design, but it has the highest work content. Also, for K equal to 0.05 and 0.1, plate 3 has the highest relative weight (total cost). It is the lightest design because it has very thin plating and light longitudinal and transverse stiffeners. It has the highest work content because it has a large number of stiffeners, requiring a large number of man-hours for the cutting, marking, and welding.

Plates 1 and 2 are stiffened in two orthogonal directions. Stiffened plate 1 is lighter than stiffened plate 2 because it has thinner plating and lighter stiffeners, but it has a higher number of closely spaced transverse stiffeners with associated high work content. Also, plate 1 has higher relative weight (total cost) than plate 2 for both values of K . Plates 4 and 5 are stiffened primarily in one direction. Stiffened plate 5 is the heavier of the two (actually it is the heaviest of all the designs) but it has the lowest work content of the two (actually it has the lowest of all the designs). For K = 0.05, plate 5 has the second lowest relative weight and for K = 0.10 it has the lowest relative weight. Thus, if the labor rates are high enough, it is better to design heavy grillages with associated small work content. Plate 4 requires higher work content because it has a larger nurnbe;of transverse stiffeners.

DESIGN	WEIGHT tonnes	RELATIVE WORK CONTENT man-hours	CERW (tonnes)	
			K = 0.05	K= 0.10
	14.7716	385.8854	34.0659	53.36
1	17.3951	260.388	30.4145	43.4339
3	14.1	425.4877	35.3	56.65
4	18.1929	308.7844	33.632	49.07
5	18.426	247.4517	30.798	43.171

Table VIE Comparison of the ‘five size-optimal stiffened plates

Discussion of reference (1) established that, based on experience, the weight difference between grillages similar to 1 and 3 has to be less than 10%. In Table VII, it is shown that the weight difference from the results obtained in this analysis is approximately 4.5%. Also, if the weight of the five stiffened plates is examined, after sorting them in ascending order, the maximum difference in weight betwem two consecutive designs is less than 15%, which represents an acceptable weight increase for equivalent structures in most ships.

EFFECT OF STRUCTURAL VOLUME ON THE LIFE TIME COST OF THE STRUCTURE

In this section, a relative cost comparison is made by adding the effects of the loss of cargo carrying capacity to the results tabulated in Table VII. Heavy designs have a smaller midship section, which results in reduced cargo carrying capacity over the lifetime of the designs. Specifically, plate 3, which is the lightest but most expensive design, is compared to plate 5, which is the heaviest and least expensive design. The cost modeling adopted for the total cost comparison of the two designs (3, 5) is the one used by Kriezis (17), modified to solve the problem addressed in this section. This model assumes that the difference between designs 3 and 5 is due only to the different material costs, the loss of cargo carrying capacity over the life of the ship of the heavier design (design 5), and the difference in fabrication man-hours for construction. Accordingly, the net cost difference is

$$NCD = \Delta_{\text{fabrication cost}} - \Delta_{\text{material cost}} - \Delta_{\text{carrying capacity cost}} \tag{15}$$

where,

$$\Delta_{\text{material cost}} = L\ (C_5 - C_3) \quad , \tag{16}$$

$$\Delta_{\text{carrying capacity cost}} = \sum_{i=1}^{N} \frac{\eta\, \Delta Q\, \eta_t\, R}{(1+r)^i} \quad , \tag{17}$$

$$\Delta Q = L\rho\ (A_5 - A_3) \quad . \tag{18}$$

The above model provides a reasonable estimate of the overall cost advantages and disadvantages of design 3 over design 5. Hence, it provides a designer with the information needed to design a particular vessel for minimum weight versus designing that vessel for minimum total cost.

The fabrication cost difference ix

$$\text{‘fabrication cost} = \text{labor rate x (work content3 - work content5)} \ . \tag{19}$$

The values of the work content for the two designs are taken from Table VII. A labor rate of $50/hour is used, which includes direct and overhead costs, and is a reasonable estimate for labor cost in the U.S.A. Substitution of those values in equation (19) results im

$$\text{‘fabrication cost} = \$8,902.00 \ . \tag{20}$$

For calculation of the carrying capacity cost difference, equations (3) and (4) are used. A maximum of 10 trips per year at full load capacity, and a ship life time of 20 years, are assumed. The freight rate per cargo tonne is $10/tonne. The rate of return – adjusted for time value of money - is assumed to be 15%, and the efficiency factor η , accounting for the cost of additional carrying capacity, is to be l.O(no costs). Finally, after calculating the cross section areas, and hence, AQ, we have:

$$\text{harrying capacity cost} = \$3,927.00 \ . \tag{21}$$

For calculation of the material cost difference, the material cost data for plates in standard production are taken from the information given in reference (17). This results in:

$$\text{material cost} = \$2,470.00 \ . \tag{22}$$

Summarizing, design 3 is $8,902 more expensive in construction, $3,927 less expensive in cargo carrying capacity, and $2,470 less expensive in materials, than design 5.

Substitution of the values for the cost differences into equation (15) yields that design 3 is $2,505 more expensive than design 5. A ship constructed by using tsventy panels of type 3 is $50,100 more expensive than a ship which has been constructed by using twenty designs of type 5. From the above simple but reasonable study, it can be concluded that the advantages of a minimum weight design, which are the low material cost and the higher cargo carrying capacity, cannot compensate for the disadvantage of high fabrication cost. So, minimizing the work content becomes the dominant factor in selecting the overall size optimum.

Although the above anrdysis does not intend to cover in detail all the variables which influence the engineering economy of a ship, a naval architect must know how to make economic studies, and how to estimate future costs of designing, building and operating ships. Hence, the conditions under which the result can be changed must be studied. That is, under what conditions may design 3 be better than design 5. For this purpose, a sensitivity analysis of the various economic parameters is performed. By making the assumption that the material and the fabrication costs do not change the most important economic parameter which can influence the remaining carrying cargo capacity costs, and hence the final result, is the rate of return adjusted for the time value of money r . This parameter includes the effect of inflation and the reward of investing or borrowing money (interest) (18). When parameter r becomes smaller, the ship which has been constructed with the panel designs of type 5 becomes more expensive regarding the cargo carrying capacity cost. Thus, there is a crossover point where a ship constructed using the panel designs of type 5 becomes more expensive overall. By performing sensitivity

analysis with respect to parameter r, it can be shown (Figure 9) that for r smaller than 7.55% design 3 becomes overall better than design 5; that is, the maximum work content design becomes the optimum one.

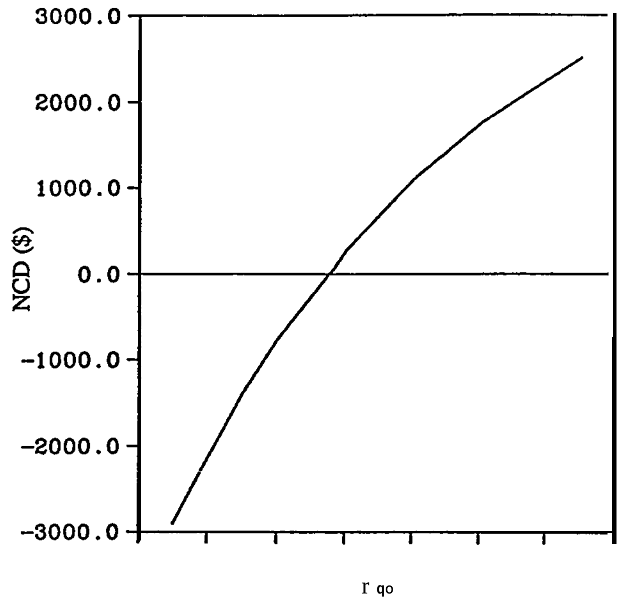


Figure 9. Net difference in cost (NCD) versus time value of money (r)

STRUCTURALLY EQUIVALENT SHAPE-OPTIMAL STIFFENED PLATES

In this section, for four out of the five stiffened plates (1, 2,4, 5), the weight, fabrication and total cost are computed for discrete values of plate thickness, standardized beam cross section, and discrete beam spacing. For stiffened plates 1 and 2 ONLY the spacing of the transverse frames is varied, because the maximum stress occurs in these beams (Figures 1, 2). Variation of the stiffener spacing is performed in such a way that salient geometric features regarding the arrangement of stiffeners are preserved. For example, in stiffened plate 1, only an even number of transverse stiffeners is considered. The location of these stiffeners is such that the number of the stiffeners is equal to the number of the spaces between them, as in the initial configuration of Figure 1. Note that end spaces are half the width of the other spaces. With regard to the variation of the thiclmess of the plate, it is assumed again that the minimum plate thickness is 5mm. Further, only standard plate thickness is considered. That is, the plate thickness can only bean integer number in millimeters. With regard to the size of the stiffeners, all 190 Bethlehem structural tees, (16) and the 7 structural tees given in reference (1) are considered for the variation of the size of the stiffeners for all configurations. The Bethlehem catalog refers to standard structural tees that are used in the United States.

Optimal Shape of Configuration 1

For plate 1, the optimum results for three different objective functions (weight, work content, total cost) and for discrete beam spacing are presented in Table VIII. In most cases, the three optima are identical. When this is not the case, a line is repeated and the appropriate optimum is shown as in the case of 16 and 2 stiffeners. All of Tables VIII-XI are constructed in that way. Graphs for the optimum configurations in Table ~ are shown in Figme 10.

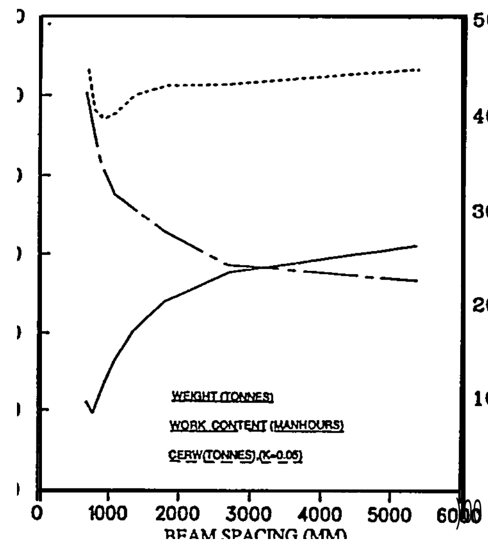


Figure 10. Optimum stiffened plate 1 for discrete beam spacing

The weight of stiffened plate 1 increases as the stiffener spacing increases. This happens because as the beam spacing increases – although the number of the transverse stiffeners being used is smaller – the size of the stiffeners, and hence their weight, is increased in order to resist the applied load. Most important, as the beam spacing increases, the thickness of the plate must be increased, and the plate accounts for most of the weight in these designs. The rate of increase of the weight, however, becomes smaller for larger stiffener spacings because the requirement for thicker plate is not very demanding for large beam spacing. So the reduction in the number of the stiffeners can compensate for a portion of the increase of the weight due to the small increase of the thickness of the plate for larger beam spacings. These are two main reasons that slightly thicker plate is needed for larger beam spacings.

First, Plate 1 is orthogonally stiffened. In Table VIII, it is shown that for transverse beam spacings up

to 1337.5mm (52.66 in), the need for plate thickness was increasing. Having in mind that the distance between the longitudinal stiffeners is fixed (1583.3mm = 62,33 in), and the St. Venant principle (the load follows the stiffer path), it can be concluded that the load will follow the longitudinal direction for transverse beam spacings up to 1337.5mm. So there is need for increased plate thickness. For transverse beam spacings greater than 1337.5mm Table VIII shows that the required increase in plate thickness is constant and equal to 3mm (0.12 in). This happens because for these beam spacings the load will follow the transverse direction which remains constant and equal to 15!33.3mm.

Second, the results in Table VIII are based on discrete optimization, and were produced subject to the limitations of standardization. If the optimization was continuous, the plate thickness needed to go from a spacing of 891.67mm (35.11 in) to a spacing of 1070mm (42.13 in) would be slightly more than 2mm (0.08 in); and not 3mm as the table shows. Therefore, the need for larger plate thickness is not incremental and equal to 3mm for beam spacings larger than 891.67mm.

The total panel weight for beam spacing of 668.75mm (26.33 in) is greater than the weight for beam spacing of 764.28mm (30.09 in). This seems to be contradictory with the rest of the curve. This contradiction exists because of the assumption that it is not possible to use plate with thickness less than 5mm, and also because there is no WT8 type of standard tee sections smaller than WT8X13. The curves of Figure 10 would be slightly different if the optimization was continuous. Finally, the optimum weight combination is the one with beam spacing of 764.28mm, light plating (5mm = 0.2 in), and 14 light transverse stiffenem (wT8x13).

An examination of the work content to spacing relationship shows that the work content decreases as the beam spacing increases because the number of transverses decreases. So, in most cases, the number of job operations decreases. The only job that requires higher man-hours is the cutting and welding of thicker plates as beam spacing increases. Actually, the work content curve becomes almost horizontal for larger beam spacings. This means that as the beam spacing increases, the increase in man-hours for cutting and butt welding of very thick plates can compensate for the decrease in man-hours for all the other jobs. Hence, the optimum work content desire is the one with b&rn spacing of 5350mm (216.63 in), thick plating

# OF TRANS, STIFF.	SPACING mm	TEE SECTION [16]	PLT. THK. mm	WEIGHT tonnes	OBJECTIVE F UNCTION WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
16	668.75	WT8X13	5	15.1	— —	36.41	65.03
16	668.75	WT6X15	5		421.31		71.03
14	764.28	WT8X13	5	14.77	385.88	34.065	73.78
12	891.67	WT8X15.5	7	16.25	345.6	33.53	71.99
10	1070	WT8X15.5	10	18.5	315.04	34.256	75.09
	1337.5	WT9X17.5	13	20.1	299.276	35.03	73.03
:	1783.33	WT9X17.5	16	21.95	273.456	35.6	73.03
4	2675	WTwc20	19	23.84	237.697	35.73	72.03
					221.995		72.03
2	5350	WTIO.5X22	22	25.59	—	36.7	71.03

Table VIIL Optimal configurations of stiffened plate 1

(22mm = 0.87 in), and only 2 heavy transverse stiffeners m=3j.

An examination of the total cost to spacing relationship shows that the optimum total cost combination is the one with beam spacing of 891.67mm, (35.11 in) light plating (7mm), and 12 transverse stiffeners (WT8X15.5). For beam spacings larger than 891.67mm, the curve shows that the total cost increases slightly but constantly as the beam spacing increases.

Finally, the above results show that the weight shape-optimum occurs for beam spacing which is smaller than the beam spacing of the total cost optimum.

Optimal Shape of Configuration 2

For plate 2, the optimum results for the three objective functions (weight, work content, total cost) and for discrete transverse spacing are presented in Table IX. Graphs for the optimum conilgumtions tabulated above are shown in Figure 11. This plate is cross stiffened, so it is expected that the behavior of the thee objective functions will be similar to the behavior of tbe corresponding functions for stiffened plate 1. The weight of the stiffened plate increases as the stiffener spacing increases. The same conclusions as for plate 1 apply for plate 2 for the weight to spacing relationship. Again, a sharp change in slope occurs for beam spacing

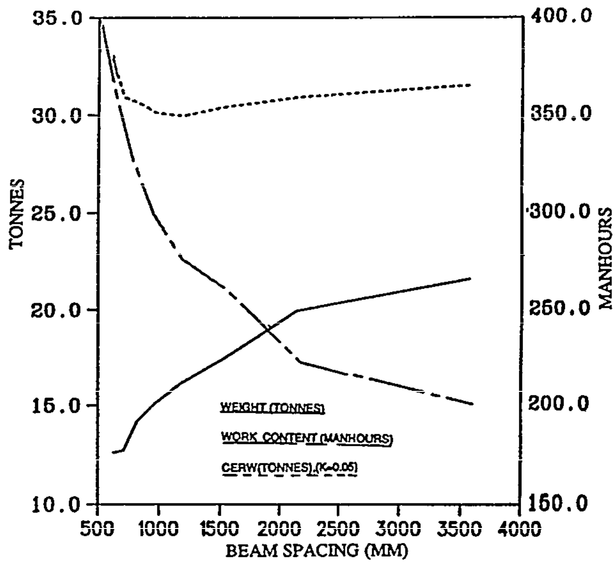


Figure 11. Optimum stiffened plate 2 for discrete beam spacing

of 713.3mm (28.08 in) because of the assumption that plate thickness of more than 5mm (0.2 in) should be used. The optimum weight combination is the one with beam spacing of 629.4mm, light plating (5mm) and 16 light transverse stiffeners (WT8X13).

The work content decreases as the beam spacing increases for the same reasons stated for plate 1. The optimum work content combination is the one with beam spacing of 3566.67mm (140.42 in), thick plating (20mm = 0.79 in) and two heavy transverse stiffeners (WT10.5X22).

The optimum total cost combination is the one with a beam spacing of 1188.9mm (46.81 in), light plating (11mm) and 8 transverse stiffeners (WT9X17.5). For beam spacings larger than 1188.9mm the curve shows that the total cost increases slightly but approximately linearly.

Finally, from the above results show that the weight optimum occurs for beam spacing which is smaller than the beam spacing of the total cost optimum.

Optimal Shape of Configuration 4

For stiffened plate 4, the optimum results for the three objective functions (weight, work content, total cost) and for discrete transverse beam spacing are presented in Table X.

Graphs for the optimum configurations tabulated above are shown in Figure 12. This plate is stiffened primarily in the transverse direction, so it is expected that the behavior of the three objective functions will be different from the behavior of the corresponding functions for plates 1 and 2.

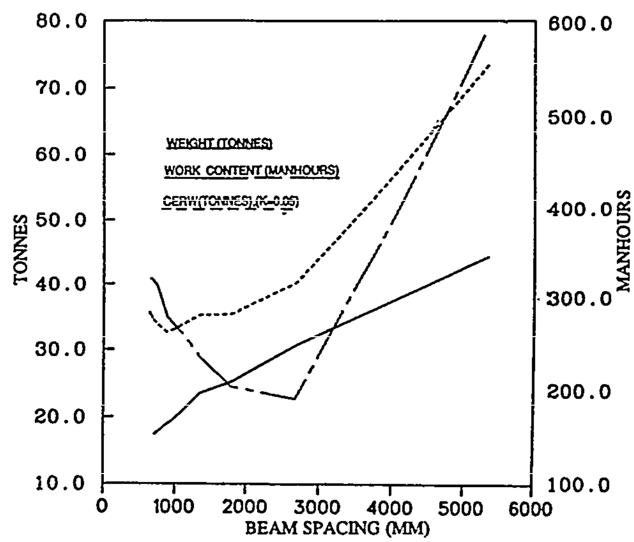


Figure 12. Optimum stiffened plate 4 for discrete beam spacing

# OF TRANSVERSE STIFFENERS	SPACING mm	TEE SECTION [16]	PLT. THK. mm	OBJECTIVE FUNCTION WEIGHT tonnes	WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
16	629.4	WT8X13	5	12.58	397.546	32.45	71.58
14	713.3	WT8X15.5	5	12.688	364.314	30.9	72.61
12	823	WT8X18	7	14.1624	329.827	30.65	74.34
10	972.7	WT9X17.5	9	15.123	300.16	30.45	73.10
8	1188.9	WT9X17.5	11	16.1526	276.517	29.97	75.16
6	1528.57	WT9X20	13	17.395	260.38	30.41	74.51
4	2140	WT10.5X22	17	19.927	——	30.96	73.44
4	2140	WT9X23	17	——	219.92	——	74.82
2	3566.67	WT10.5X22	20	21.58	198.13	31.489	75.03

Table IX: Optimal configurations for stiffened plate 2

# OF TRANSVERSE STIFFENERS	SPACING mm	TEE SECTION mm [1]	PLT. THK. mm	OBJECTIVE FUNCTION WEIGHT tonnes	WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
14	764.28	600X6-150X8	8	17.1	——	——	75.03
14	764.28	550X10-250X20	8	—	308.78	33.632	73.99
12	891.67	550X10-250X20	11	18.96	275.82	32.5	75.06
10	1070	550X10-250X20	15	20.47	261.18	33.53	74.03
8	1337.5	700X10-250X30	18	23.46	234.13	35.17	73.99
6	1783.33	700X10-250X30	23	25.16	202.08	35.32	79.03
4	2675	700X10-250X30	33	30.57	190.25	40.1	75.06
2	5350	1200X12-400X30	52	44.31	583.86	73.5	75.06

Table X: Optimal configurations for stiffened plate 4

The weight of the plate increases as the stiffener spacing increases. The rate of increase of the weight doesn't drop for larger stiffener spacings, as is the case of plates 1 and 2. The main reason is that plate 4 is unidirectionally stiffened, which means that the requirement for larger thickness of the plate is very demanding for large beam spacings. So, for a transverse beam spacing of 5350mm (2.06 in), the thickness of the plate must be 52mm (2.05 in), which is 19mm (0.75 in) greater than the required plate thickness for transverse beam spacing of 2675mm (105.3 in). In plates 1 and 2 the corresponding increase was only 3mm (0.12 in). The optimum weight combination is the one with beam spacing of 764.28mm (30.09 in), light plating (14mm = 0.55 in) and 14 light transverse stiffeners (web 600X6mm, flange 150X8mm).

For small transverse beam spacings, the work content decreases as in the cases of plates 1 and 2. The reduction in the number of transverse stiffeners afforded by increased spacing saves considerable time. The rate of the work content reduction, however, becomes smaller as the beam spacing increases, because the requirement for a thicker plate increases the number of man-hours for cutting and butt welding the plate. In fact, for transverse beam spacing greater than 2675mm (105.31 in), the objective function of work content increases significantly, because many man-hours are needed for cutting and multiple pass butt welding 52mm (2.05 in) thick plate needed for a beam spacing of 5350mm (210.6). So, for a large beam spacings the size of the stiffener has a small effect on the fabrication time of this stiffened plate. The optimum work content combination is the one with transverse beam spacing of 2675mm, 33mm (1.31) plate thickness, and transverse stiffeners of the type: web 700X10mm, flange 250X30mm.

The optimum total cost combination is the one with beam spacing of 891.67mm (35.11 in), light plating (11mm = 0.43) and 12 light transverse stiffeners (web 550X10mm, flange 250X20mm). Again, the total cost optimum occurs for a beam spacing which is larger than the beam spacing of the weight optimum.

Optimal Shape of Configuration 5

For plate 5, the optimum results for the three objective functions (weight, work content, total cost) and for discrete longitudinal beam spacing are presented in Table XI.

# OF TRANSVERSE STIFFENERS*	SPACING mm	TEE SECTION mm [1]	PLT. THK. mm	OBJECTIVE FUNCTION WEIGHT tonnes	WORK CONTENT man-hours	CERW tonnes	MAX. STRESS MPa
10	791.67	550X10-250X20	11	18.426	247.45	30.8	71.23
8	950	550X10-250X20	14	19.01	215.55	29.78	75.03
6	1187.5	700X10-250X30	16	20.73	192.39	30.34	75.03
4	1583.33	700X10-250X30	21	22.9	159.67	30.88	74.82
2	2375	870X12-360X30	30	27.64	133.65	34.3	73.03

*Does not include the middle longitudinal keel stiffener

Table XI: Optimal configurations for stiffened plate 5

Graphs for the optimum configurations tabulated above are shown in Figure 13. Plate 5 is a unidirectionally (longitudinally) stiffened plate, so the results are expected to be similar to the results obtained for plate 4. For this discrete shape optimization, the middle longitudinal keel stiffener was kept the same as shown in Figure 5 because the keel stiffener provides strength and acceptable stresses at the clamped ends of the other longitudinal stiffeners.

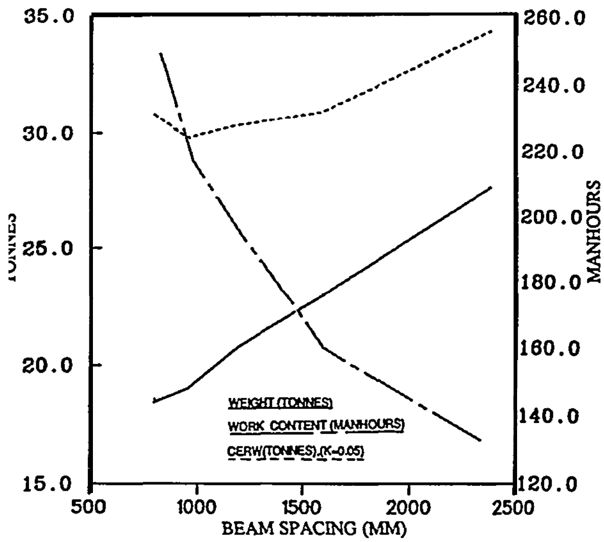


Figure 13. Optimum stiffened plate 5 for discrete beam spacing

The weight of the stiffened plate increases as the stiffener spacing increases, with approximately the same rate as the rate of the weight increase of plate 4. Thick plate is required for large beam spacings for the same reasons as those for plate 4. The optimum weight combination is the one with a beam spacing of 791.67mm (31.17 in), llmm (0.43 in) plating and 10 light longitudinal stiffeners (web 550X10mm, flange 250X20mm).

The work content decreases as the longitudinal beam spacing increases. The rate of the work content decrease becomes smaller for large beam spacings for the same reasons as those for plate 4. The optimum work content combination is the one with longitudinal beam spacing of 2375mm (93.50 in), 30 mm (1.18 in) plating and 2 heavy longitudinal stiffeners (web 870X12mm, flange 360X30mm).

Finally, the optimum total cost combination is the one with longitudinal beam spacing of 950mm (37.40 in), 14mm (0.55 in) plating and 8 light longitudinal stiffeners (web 550X10mm, flange 250X20mm). Again, a larger stiffener spacing was found to be optimum for the total cost objective function compared to the weight objective function.

CLOSING REMARKS

Five stiffened plate configurations, widely used in shipbuilding, were studied to assess their structural integrity and to optimize them. It was found that four of those five panels did not meet the structural strength criteria established in this work. New designs of minimum total cost subject to stress, buckling, and standardization constraints were produced by discrete size optimization. Four of those five designs were further improved in shape optimization. Among all the structurally equivalent configurations of the five different stiffened plates, it was found thah i) The minimum weight design is stiffened plate 2 with 16 transverse stiffeners WT8X13, a transverse stiffener spacing bf 629.4mm (24.78 in), and plate thickness equal to 5mm (0.2 in). ii) The minimum work content design is stiffened plate 5 with 2 longitudinal stiffeners of web 870X12mm, flange 360X30mm, a longitudinal stiffener spacing 2375mm (93.50 in); and plate thickness equal to 30mm (1.18 in). iii) The minimum total cost design is stiffened plate 5 with 8 longitudinal stiffeners web 550X10mm, flange 250 X20mm; longitudinal stiffener spacing of 950mm (37.40 in); and plate thickness equal to 14mm (0.55 in). Other important qualitative conclusions are the following.

1. The weight of both cross stiffened plates (1 and 2) and unidirectionally stiffened plates (4 and 5) increases as the beam spacing increases. The rate of the weight increase, however, is different.

2. In general, the work content for stiffened plates decreases as the beam spacing increases. The rate of the work content reduction becomes smaller for larger spacing. In the case of stiffened plate 4, for beam spacings greater than a certain value, the work content increases.

3. The optimum beam spacing using total cost as the criterion was found to be 127 mm (5 in) to 559 mm (22 in) larger than the beam spacing for the weight optimum design.

Discrete optimization was performed in this study. The following question arises at this point. Will the discrete optimization performed in this work produce the optimal design sought, or is continuous optimization necessary? Continuous structural optimization, of course, would ignore standardization and call for customized plate and stiffeners. Some of the reasons why discrete optimization will provide applicable results are provided below.

Stiffener spacing is a naturally discrete variable. Assuming this variable to be continuous in a continuous optimization process, and then using the nearest discrete value would produce suboptimal results.

The number of discrete values of the other two variables used in this work are high enough to give an adequately dense matrix of designs. All integer plate thicknesses in millimeters greater than 5mm (0.2 in), 190 Bethlehem tees (16), and the 7 stiffeners in

reference (1) are considered. So, the optimal design that would be produced by continuous optimization is expected to be very close to that produced by the process developed in this paper.

Indeed, it is possible at the end of the discrete optimization process to measure how close the discrete optimum is to the continuous optimum without computing the latter. Monotonicity concepts in theoretical optimization, as well as common sense, point to the fact that the combined secondary and tertiary stress constraint must be active (19). That is, the maximum stress in psi in the structure must be 75.85 (11,000 psi). The actual stress value for the discrete optima in Tables VIII-XI are shown in the last column of each table. Obviously, reduction of plate thickness or stiffener cross-section would reduce the total structural weight, and produce a better design. Nonstandard plate thicknesses and stiffeners have to be used in such a case.

If standardization is mandatory - as is assumed to be the case in this paper- then discrete optimization is a better method to use. The alternative of applying continuous optimization and then selecting the nearest combination of plate-stiffener, cannot produce a superior design. On the contrary, if several discrete (standard) combinations are possible alternatives, the incorrect choice may k made.

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